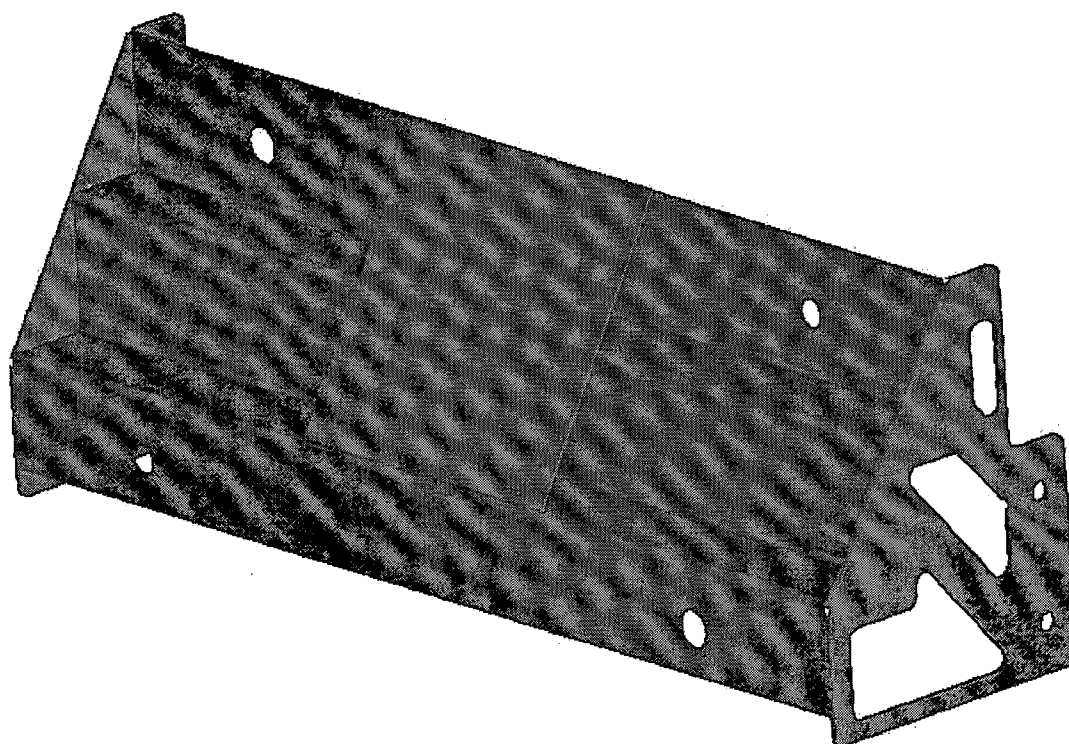


# Understanding Mechanical Design With Respect to Manufacturability



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### Abstract

**At the NASA Prototype Development Laboratory in Kennedy Space Center, Fl, several projects concerning different areas of mechanical design were undertaken in order to better understand the relationship between mechanical design and manufacturability. The assigned projects pertained specifically to the NASA Space Shuttle, Constellation, and Expendable Launch Vehicle programs. During the work term, mechanical design practices relating to manufacturing processes were learned and utilized in order to obtain an understanding of mechanical design with respect to manufacturability.**

### Nomenclature

$A$	= a variable that represents an arbitrary dimension of a flat section of sheet metal in inches
$c$	= the location of the centroid for a specified shape in inches
$L_t$	= total flat length in in. regarding an entire piece of sheet metal
$B_A$	= bending allowance in in.
$t$	= location of the neutral sheet measured in in. from the inner bend surface of a piece of sheet metal
$T$	= thickness of a piece of sheet metal in in.
$R$	= inner bend radius in in.
$\theta$	= bend angle in degrees
$K$	= represents the ratio of the neutral sheet location to sheet metal thickness
$h$	= height in in.
$M$	= bending moment of a load bearing system in lb/in
$\sigma_m$	= ultimate shear strength in ksi
$b$	= base length in in.
$v$	= beam deflection in in.
$P$	= a point load or distributed load in lb
$x$	= distance in the horizontal direction in in.
$I$	= moment of inertia in lb*in <sup>2</sup>
$\phi$	= diameter of circular object in in.

## I. Introduction

For a designer, it is important to know the basic functions of the concept being designed. Simple hand calculations for load-bearing concepts can aid the designer, so that a design can execute its function appropriately if/when the design is fabricated. Also, it is imperative that the designer makes the design intent clear for machinists, other engineers, and supervisors who are involved in the project. If a design is being sent out to machinists who are not affiliated with the designer's company, and the design intent is unclear, a lot of time and money could be lost.

At the NASA Prototype Development Lab, mechanical designers strive to provide innovative designs in an efficient manner for a multitude of projects including the Space Shuttle, Constellation, and Expendable Launch Vehicle programs. This efficient manner of design includes practical designs that recognize cost and manufacturing. While working alongside of NASA engineers and ASRC Aerospace support contractors during my internship, I aspired to learn how to design in a more practical way, so that costs are kept low and exceptional work is delivered. Thus, learning the practical methods of mechanical design can help one make a contribution to the goals of NASA and human space flight.

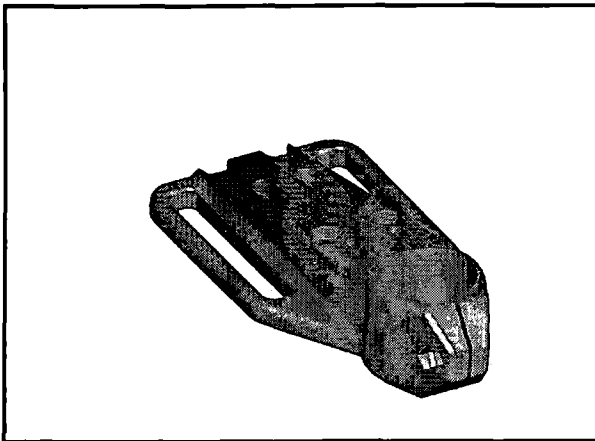
## II. Description of Activities

Various components of several projects were modeled and manufactured during the work term. Specifically, the projects furthered during the work term included the Portable Handheld Window Inspection Device (PHOWID), Orion Command Module (CM) full-scale mock-up, Habitat Demonstration Unit (HDU), and Portable Communications Terminal (PCT) projects. For each of the aforementioned projects, the customer expressed requirements, and each concept was designed to accommodate those requirements.

### A. PHOWID Bracket Design

The PHOWID apparatus is a tool that allows engineers and corrosion specialists to digitally map out imperfections in various materials by using a spectral analyzer. More importantly, PHOWID provides an accurate and simple method for analyzing the space shuttle's window damage after each mission, so that structurally compromised windows can be replaced or repaired.

The existing PHOWID design yielded a spectral analyzer pen held by a metal bracket, which all mounted to a metal base plate. The customer requested a new base plate design that could accommodate a much larger spectral analyzer pen and bracket. The customer provided a larger bracket as a design reference, but this bracket was eventually re-designed as part of the actual base plate. See Fig. 1 for more details. It was then understood that a Fused Deposition Modeling (FDM) rapid prototyping machine would be utilized for the prototyping because it would require less machine time, and the prototype would be light in weight. FDM machines fabricate designs using plastics that are layered on top of each other. For this project, the bracket was fabricated out of an Acrylonitrile butadiene styrene (ABS) polycarbonate blend of plastic.



**Figure 1. Final PHOWID Bracket Prototype CAD Model.** *Isometric view of the latest version of the bracket.*

### B. Orion CM Mock-up Design

Two mocks were designed for a full-scale Orion CM mock-up—a service panel mock-up and a mock-up of a 60-degree portion of the command module's outer-surface. The customer provided reference CAD Computer Aided Design (CAD) models for both of the concepts.

#### 1. Service Panel Mock-up

Given a CAD model of the most recent design of the service panel, I kept the same dimensions and made a simplified version. Certain cosmetic features of the given model seemed more complicated to manufacture than to model, so these attributes were noted and re-designed to reduce machine time.

At the time, there was an existing service panel mock-up with components that attached the panel to the rest of the CM mock-up. These components included a foam block that used magnets to adhere to the full-scale

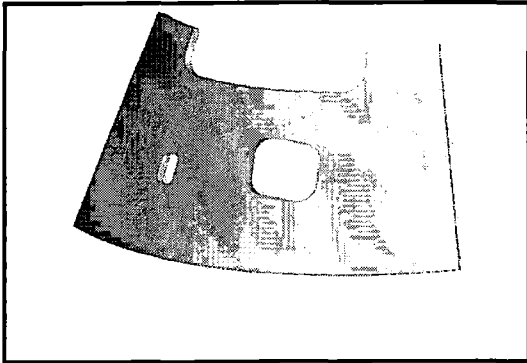
mock-up. Also, this foam block housed two shafts, washers, and knobs that fastened onto two threaded rods. The customer stated that I could use existing components in my new concept for the service panel mock-up. The aforementioned components were re-modeled, so that they could be used in my assembly of the CM service panel mock-up.

When the design was completed, I created an isometric drawing that portrayed the service panel mock-up, so that the separate pieces of sheet metal could be welded. Once the welded section of the service panel was complete, I assembled the weldment and existing components by hand.

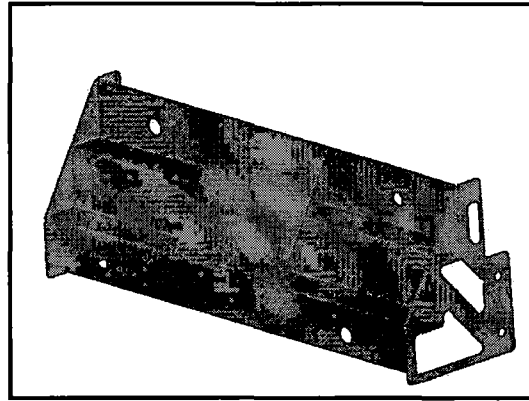
## 2. 60-Degree Outer Skin Mock-up

The customer provided the most recent CAD model of the Orion command module. From this model, the requested section was located and used as a reference for the design of the full mock-up's outer-surface. By referencing the geometry of the given model, I could ensure that the mock-up would be exactly like the current Orion command module design.

After designing the outer-surface, a way to support that surface, and a method to attach it to the existing mock-up, I defined a materials list by selecting lightweight materials. The customer expressed that the outer skin could be flexible. After researching materials, polyethylene foam seemed to be a promising choice. The polyethylene foam provided a lightweight, flexible material that could be bent to the appropriate radius that the Orion command module required.



**Figure 3. Assembled CM outer-surface model.**  
*A 60 degree section of the Orion CM designed based off of models provided by Lockheed Martin.*

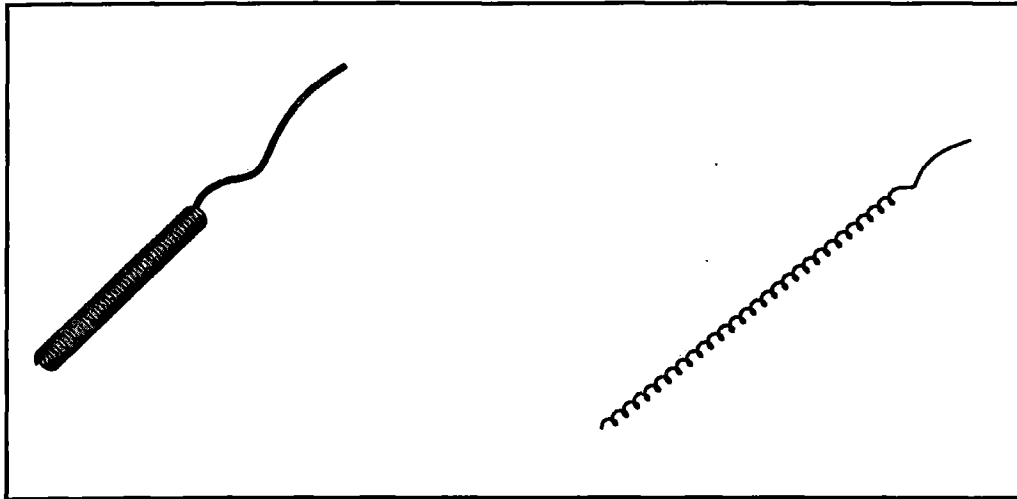


**Figure 2. Service Panel Weldment Isometric View.**

## C. Portable Communications Terminal Component Design

The PCT project is an apparatus that is designed to record data from a simulated lunar surface. After the construction of the design, the PCT will be subjected to harsh weather conditions in the desert.

Given the dimensions and specific design criteria provided by the customer, several concepts for a camera-lifting system were designed for this project. My task was to design a way to store and release 96 in. of cat5 cable. The initial concepts utilized spring-loaded pulley systems and basic cable receptacles. However, after talking to a custom cable shop in California, I discovered that a coiled cat5 cable with the ability to extend out 96 in. and retract to 20 in. was available. This cable would fit the needs of the customer, for it would be weather resistant. Also, the cable would be easier to store because it would have the ability to retract into a cable storage receptacle.



**Figure 4. Coiled Cat5 Cable Storage.**  
*Left: Retracted cat5 cable. Right: Extended cat5 cable.*

#### **D. Habitat Demonstration Unit Load Bearing Bracket Design**

The proposed Habitat Demonstration Unit (HDU) workstation currently being designed by NASA mechanical engineers consists of an engine hoist, a worktable, and adjustable arms that can hold a laptop computer and a tool tray. My involvement in this project included modeling support and the preliminary design of a load-bearing bracket.

### **III. Discussion of Results**

Manufacturing processes and their relation to engineering mechanics can be found in any reference machinery literature such as the Machinery's Handbook. Design and manufacturability correlate because the fabrication of a design relies on manufacturing processes executed by machinists. Knowing about these manufacturing processes during the design phase can lead to success.

According to the Machinery's Handbook, manufacturing processes include, but are not limited to: punches, dies, and press work; electrical discharge machining; iron and steel castings; metal joining, cutting, and surfacing; welding; laser work; hard facing; cutting metal; files and burs; and surface treatments for metals<sup>1</sup>. All of the design projects assigned during the work term had specific manufacturing needs based on the materials of a design and the design itself.

#### **A. Aluminum Sheet Metal Bending and Welding for Orion CM Mock-up Design**

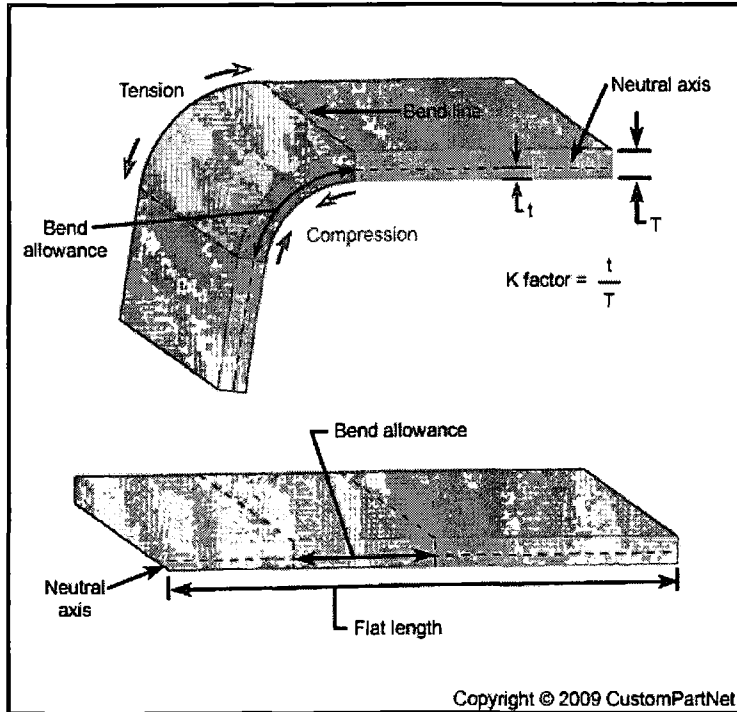
For my design of the service panel mock-up, it was determined that 1/16 in. aluminum sheet metal would need to be bent and welded to 1/8 in. aluminum sheet metal. The purpose of having the service panel mock-up on the CM mock is to provide a more realistic panel that contains actual bulkhead connector fittings, so that the accessibility to the service panel can be determined by connecting flexible hoses to the mock-up. The base model used for the recent service panel design contained two 90° bends.

##### *1. Bending Allowances and the K-factor*

Modeling two 90° bends for the sake of modeling would be easy, but understanding what the bends actually represent to a machinist and the design is more complex and worth representing in a CAD model. The actual inner and outer radii pertaining to a 90° bend depend on  $K$  (the K-factor).  $K$  represents where the compression of the sheet metal turns into tension based on the material's properties<sup>2</sup>. The compression and tension caused by the bending changes the length of the original flat sheet metal, and this discrepancy must be addressed. In the case of the service panel mock-up, a machinist needs to know the dimensions of the flat sheet metal that is going to be bent. There are several ways of accounting for this discrepancy of sheet metal length, otherwise known as the bend allowance.

Specifically for aluminum and other soft steels:

$$L_t = (.55 \times T) + (1.57 \times R) \text{ (Ref. 1)} \quad (1)$$



**Figure 5. Tension and Compression with respect to K.**  
The neutral axis location portrayed on a piece of flat sheet metal vs. a bent piece of sheet metal. NOTE: The location of the neutral axis does not change.

Another way of accounting for the tension and compression of the sheet metal is to calculate the bend allowance.

$$L_t = A + B_A \text{ (Ref. 2)} \quad (2)$$

The location of the neutral axis of a piece of sheet metal can rely on the grain of the material among other things<sup>2</sup>, and this is needed to calculate the bend allowance need for Eq. (2).

$$B_A = (\theta\pi(R + KT))/180 \text{ (Ref. 2)} \quad (3)$$

Also, there are bend tables that state the extra length of straight stock necessary for a 90° bend based on the radius of the bend, the thickness of the material, and the actual material. The most effective way to determine how much straight material you will need is to bend a test piece of material and measure the loss of material.

When modeling the 90° bends I calculated a bend allowance and used accurate bend radii based on my findings. However, when it came time to fabricate the service panel, a test piece of aluminum sheet metal was bent before cutting the

piece of sheet metal required for the actual weldment. Also, this process was repeated for a set of four mounting brackets used to connect the outer skin section of the full Orion mock-up to the existing aft bay section.

## 2. Welding Aluminum sheet metal

In the design process, it is important to know the mechanical properties of the materials you will be welding. Initially, for the Orion CM mock-up, I chose to use all 1/16 in. thick 5052 aluminum alloy. However, after speaking to one of the experienced NASA welders about the warping of sheet metal due to the high welding temperatures, it was understood that a thicker material would have to be used for certain sections.

## B. Load Bearing Bracket and I-beam Design for HDU Workstation

A load of 220 lb is proposed to be suspended from a trolley that moves along an I-beam. The trolley comes with pins that are made to hold a bracket. However, the bracket that comes with the trolley will be inadequate for the customer's needs. A new bracket will be designed in order to hold a hoist and its maximum load.

### 1. Information for Preliminary Analysis

The hoist itself weighs 50 lb. The maximum load that the hoist can hold is 220 lb. The hoist houses a motor that drops a cable down one side of a cylinder. A 67.66 in. long I-beam will feel the load. The I-beam's cross-section is represented in Fig. 6.

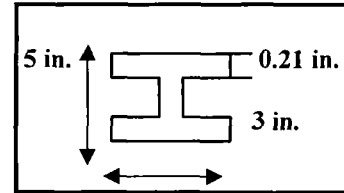


Figure 6. Cross-Section of the I-beam.

It was decided that two plates would be welded together to make the shape of the bracket that would connect the hoist to the I-beam. At this point, one would need to know the thickness of the bottom plate, so that a 220 lb load could be held by the bracket.

Using the following equations, the thickness of the bottom plate of the bracket was calculated:

$$\sigma_m = (|M| c)/I \text{ (Ref. 3)}$$

$$I = (1/12) * b * h^3 \text{ (Ref. 3)}$$

Being that this cross-section is rectangular,

$$c = h/2 \text{ (Ref. 3)}$$

$$\sigma_m = [|M| (h/2)] / [(1/12) * b * h^3] \text{ (Ref. 3)}$$

The thickness of the plate was found. After this preliminary calculation, the top portion of the bracket was taken into account. Being that the shape including the top portion of the bracket was not rectangular, the location of the centroid was found using parallel axis theorem.

At this point in my hand calculations, it was discovered that the load carried by the hoist could create torsion because the load would be off center. The calculations and design for the bracket are not complete.

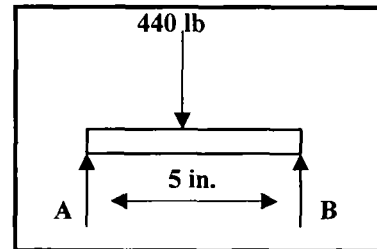


Figure 7. Free Body Diagram of Bottom Plate of the T-shaped bracket.

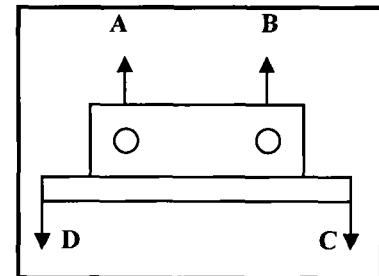


Figure 8. Free Body Diagram of the hoist bracket.

#### IV. Conclusion

During this 15-week internship, I learned how important the manufacturing process is to the design process. In addition to a new sense of respect for the entire prototyping process, I learned the basics of ProEngineer, Wildfire 3.0. By seeing projects completed from design, fabrication and finally, assembly, one can have an accurate understanding of the importance to get a design right the first time. Several man-hours are spent machining parts that are supposed to serve a purpose. Everyone makes mistakes; however, most mistakes could be avoided by asking oneself simple questions about how a part will be manufactured.

Personally, I hope to continue thinking about mechanical design in a practical way. Also, I would like to keep up with my modeling skills and learn more about the ProEngineer software, so that I can model things more efficiently. I feel very privileged to have had a chance to work alongside of the country's most talented engineers and machinists.

### Acknowledgments

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